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Source and origin of glacial paleovalley-fill sediments (Upper Ordovician) of Sarah Formation in central Saudi Arabia

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Abstract A study was carried out on the combination of petrographies, geochemistry (major and trace), weathering and the digenesis of 31 sandstones samples to determine their provenance and depositional tectonic setting of sedimentary basins. Based on the composition of Detrital grains (point counting), most of the Sarah sandstones were classified as quartz arenites types (99% on an average). The petrographic data indicated that the resultant mature sandstones are derived from recycled and craton interior tectonic provenance. Tectonic setting discrimination diagrams based on major elements suggest that sandstones were deposited in a passive margin and polycyclic continental tectonic setting. The relationship between K_2O/Na_2O ratio and SiO_2 showed that the Sarah sandstone samples fall into the passive margin field. The chemical index of alteration (CIA=63.84%) of sandstones suggested moderate weathering or reworking in the area. The concentration of trace elements indicates that the sediments were probably derived from the mixed sedimentary-meta sedimentary provenance and changes in sedimentary process due to climatic variations. The main diagenetic events were in the form of cements, which occur as grain coats and as pore fillings. An integrated approach showed that the parent area of paleovalley-fill sediment is probably a complex of granite, metasedimentary and pre-existing sedimentary rocks.

Keywords Glacial paleovalley · Provenance · Geochemistry · Weathering · Diagenesis

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Introduction

The interrelationship between petrography and chemical composition of sandstones is a useful tool to characterize the provenance and tectonic setting of sediments basin (Dickinson and Suczek 1979; Dickinson et al. 1983; Bhatia and Crook 1986; McLennan et al. 1993 and Armstrong-Altrin et al. 2004). However, other factors such as depositional environment (Espejo and Lopez Gamundi, 1994), climate (Suttner et al. 1981) and diagenesis (McBride 1987) were also modified framework composition of sandstones. The interpretation of the tectonic setting of sandstones, based on the detrital modes, was successfully carried out by Dickinson and Suczek (1979); Dickinson et al. (1983).

The chemical composition of sedimentary rocks is interplay between the type of source rocks, source area weathering, and diagenesis (Nesbit and Young 1989; Milodowski and Zalasiewiez 1991 and McLennan et al. 1993) as long as the bulk composition of a rock is not altered. The geochemical analysis is a valuable tool in the study of even matrix-rich sandstone (McLennan et al. 1993). The concentration of trace and major elements are different for different types of rocks and environments (McLennan et al. 1993; Bhatia 1983 and Bhatia and Crook 1986). Bhatia (1983) classified the tectonic setting of sedimentary basin containing significant wakes into four main types such as oceanic island arc, continental island arc, active continental margin and passive margin. Bhatia (1983) discriminate function has been used by recent researcher like Zimmermann and Bahliburg (2003); Armstrong-Altrin et al. (2004) and Jafarazadeh and Hosseini-Barzi (2008). The sandstones from different tectonics can be distinguished by the high and low concentrations of the immobile oxides (SiO_2 and TiO_2) and mobile oxides (CaO and Na_2O). The effects of weathering on the sediments were recorded as a

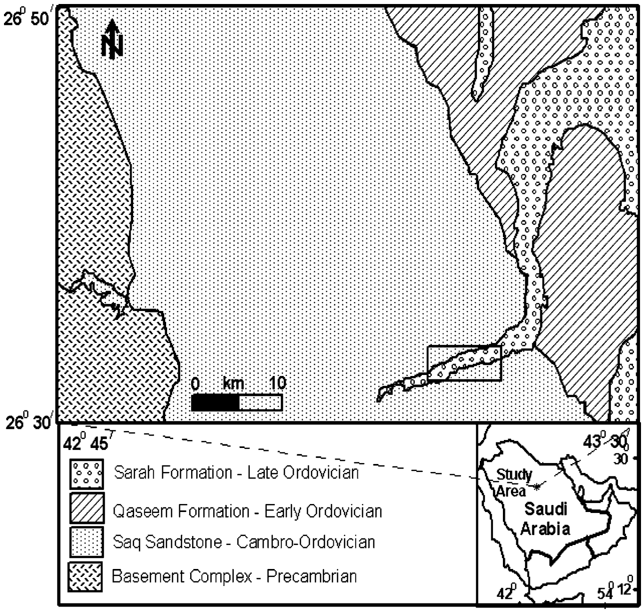


Fig. 1 Geological map of study area (after Manivit et al. 1986)

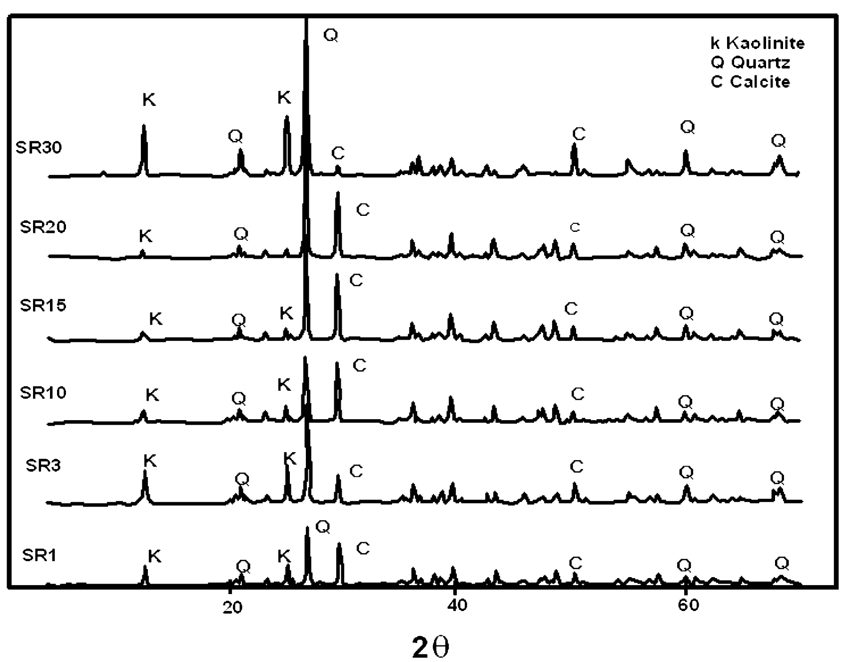
paleoclimate index (Nesbit and Young 1982; Chittleborough 1991). The study area, Sarah Formation (26°30′15″; 43°03′56″), incised valley sequence is scattered over more than several kilometres width and is exposed in Qaseem Region of Central Saudi Arabia (Fig. 1). As far as stratigraphical position is concerned, earlier investigators like Clark-Lowes (1985a,b) and Al-Laboun (1982, 1986) agreed that Sarah was a member of Tabuk Formations. But Vaslet (1989) revised the stratigraphy and recognized it as Sarah Formation. In general, the Sarah Formation comprises mostly of fine to medium grains, trough and planner cross-bedded sandstone in a paleovalley. Sometimes, the paleovalley's sediment cuts the Hanadir member of Qaseem Formation and Saq sandstone as deep as 400 m. The thickness of the Formation depends on its position within the paleovalleys. It is about 70 m thick in this area. Fluvial, estuarine and tide-dominated lithofacies associations were identified in various parts of the valley-fill (Senalp 2006). The Formation consists of mostly sandstone deposited in fluvial, glacial and marine environment. Clark-Lowes (1985a) investigated around the present study area which was based on field information leading to sedimentology of the paleovalley sediments. He concluded that this area has major evidences of glacioeustatic sea level fluctuations in the Late Ordovician time, which resulted in the cutting and filling of large-scale paleovalley. Sarah Formation (Ashgillian glacial deposits) also has economic significance due to the presence of petroleum reservoir in Saudi Arabia and North Africa (Clark-Lowes 1985a,b).

The main aim of this paper was to utilize a combination of petrographical and geochemical methods to study paleovalley-fill sediments provenance and tectonic setting.

Geology and physiography of the study area

Proterozoic rocks are located in this area along the north-eastern margin of the Arabian Shield. They are overlapped by Cambro-Ordovician Saq sandstone and Quaternary alkali-olivine basalt of the Harrat. The present Sarah sandstone is laying unconformably upon the Cambrian to Arenigian Saq Formation. Manivit et al. (1986) reported that basal surface of Sarah Formation is rugged and consists of fine to medium grains which are gritty and pebbly. The

Fig. 2 XRD graphs of Sarah sandstone



stratigraphical position of Sarah Formation is in between the Late Caradocian (and Ashgillian) and the Middle Llandoverian (Beuf et al. 1971; Spjeldnaes 1981). Since the glaciation period was very short in Saudi Arabia (0.2–1 ma), deglaciation and associated tectonism-triggering deformation, did not last more than a few hundred thousand years (Turner et al. 2003).

In the early Protezoic times, the Arabian Peninsula was a part of the Gondwana and laid at low to high latitudes in the Southern hemisphere. Bell and Spaak (2006) reported that four distinct glacial events are recorded in the sedimentary record of the Arabian Peninsula. It was first reported in Saudi Arabia by McClure (1978). These glaciers were correlated with the position of the Arabian plate related to Gondwana-land ice caps during the Early Silurian–Late Ordovician. The glacial outwash sediments in the subsurface in the central part of the country gave a new idea about the depositional environment of the other basins in the area. The glacier was further characterized by two major phases of ice i.e. advance and retreat (Vaslet 1990) which resulted in the formation of Sarah Formation (Miller and Mansour 2007). The characteristics of Sarah Formation showed close proximity with the outcrops of North America. Beuf et al. (1971) reported that in Algeria, the upper Ordovician paleovalleys cutting was at a depth of about 300 m. In Libya, similar deposits were reported in Murzuiq basin by Smart (2000).

Sampling and analytical techniques

Thirty-one unweathered sandstone rock samples were collected from one stratigraphic section for thin-section

Table 1 Model analysis of sandstone samples of Sarah Formation

Sample no.	Mono Quartz (%)	Non-undulos Quartz (%)	Undulose Quartz (%)	Polycrystalline Quartz (%)	Total Quartz (%)	Feldspar (%)	Rock fragments (%)
SR01	90.0	26.0	64.0	9.0	99.0	–	1.0
SR02	97.3	16.3	79.7	2.9	98.9	–	1.0
SR03	96.1	17.8	79.2	1.8	98.8	–	1.0
SR04	95.5	9.1	86.4	3.1	98.6	–	1.0
SR05	96.0	35.1	60.8	2.7	98.7	–	1.0
SR06	94.2	20.7	73.5	5.0	99.2	–	1.0
SR07	93.8	23.3	69.2	6.0	98.5	–	1.0
SR08	91.0	26.7	79.5	9.0	100.0	–	–
SR09	96.2	21.3	74.9	2.8	100.0	–	–
SR10	94.3	23.2	69.1	5.8	98.1	–	1.9
SR11	96.0	19.0	77.0	3.7	99.7	–	0.3
SR12	91.0	18.0	73.0	8.0	99.0	–	1.0
SR13	92.3	13..1	82.7	3.9	99.7	–	0.3
SR14	98.2	20.7	77.5	1.8	100.0	–	–
SR15	98.6	13.7	84.9	1.4	100.0	–	–
SR16	95.4	10.5	84.9	2.6	100.0	–	–
SR17	98.2	14.2	84.0	1.8	100.0	–	–
SR18	98.6	28.5	70.1	1.4	100.0	–	–
SR19	98.7	18.0	80.7	1.3	100	–	–
SR20	94.1	15.8	78.2	4.7	98.8	–	1.2
SR21	96.5	10.1	86.4	3.5	100	–	1.0
SR22	96.0	30.1	65.8	2.7	98.7	–	1.3
SR23	94.2	20.7	73.5	5.0	99.2	–	0.80
SR24	97.5	24.3	73.2	1.5	98.5	–	1.5
SR25	96.0	30.5	65.5	4.0	100.0	–	–
SR26	97.2	21.7	75.5	2.8	100.0	–	–
SR27	96.6	24.5	72.1	3.4	100.0	–	–
SR28	97.1	15.1	82.0	2.9	100.0	–	–
SR29	98.0	20.0	78.0	2.0	100.0	–	–
SR30	94.3	13.6	80.7	2.6	100.0	–	–
SR31	95.2	13.6	81.6	4.8	100.0	–	–

analysis. Mineral composition of the samples was carried out using the point-counting method of Gazzi and Dickinson as described earlier by Ingersoll et al. (1984). Detrital and authigenic minerals and cements were identified using a combination of thin sections and X-ray diffraction methods. Sandstone samples were analyzed for major and trace elements by ALS Chemex Lab, Canada.

Results and discussion

The sandstone samples were mainly composed of detrital grains (total quartz and rock fragments) and cement (clay, iron, carbonate and silica; Fig. 2). Sandstone mainly consisted of quartz including monocrystalline quartz type, undulose (60.8–86.4%) and non-undulose (9.1–35.1%), polycrystalline quartz (1.3–9.0%) and rock fragments (00–1.5%; Tables 1 and 2). On the basis of detrital composition, the sandstones fall in Quartz arenite group (Folk 1974). There was no significant variation in the detrital sandstone composition within the Formation. Majority of the quartz grains were either corroded or replaced quartz grains and in some cases cements were also forming bridges between the detrital grains (Fig. 3a). The well-rounded polycrystalline quartz consisted of three or less than three crystals. But most of the inter-crystal contacts were either straight or granulated boundaries (Fig. 3b). Sandstone and chert were the only sedimentary rock fragments found in Sarah sandstone (Fig. 3c, d). The grain contact in the sandstones was a point and long. Floating grains were observed in most of the samples. The analytical results showed that the cements are dominated by calcite, but in some cases, the silica cement is also common in the form of quartz grains as single and double overgrowths (Fig. 3e). In some grains, diagenetically formed cements etching even quartz overgrowths were found (Fig. 3f). The Quartz overgrowths were absent around the quartz grains which were coated with relatively thick layer of cements.

The result of major and trace geochemistry of Sarah sandstone is presented (Tables 3 and 4). Table 3 shows that most of the sandstones were rich in SiO_2 (98.32% wt. average) and low in Al_2O_3 (1.24% wt. average), K_2O (0.099% wt. average), Fe_2O_3 (0.046% wt. average), CaO (0.33% wt. average), MgO (0.083% wt. average), TiO_2 (0.148% wt. average), Na_2O (0.033% wt) and MnO (0.024% wt. average).

The concentration of trace elements showed that Sarah sandstone is rich in Ba, Cr, Pb, Sr and Zr. The mean concentration of the dominant elements in sandstones was Sr (31.0 mg/l) followed by Ba (25.48 mg/l), Pb (13.59 mg/l), Zr (3.67 mg/l) and Cr (2.58 mg/l) as shown in Table 4.

Quartz typology is one of the sources to study provenance of sandstone in the absence of feldspar and scarcity of rock fragments (Basu et al. 1975). The domination of monocrystalline quartz (>90%) as compared with polycrystalline quartz (3.5%) resulted from reworking of polycrystalline quartz and other labile minerals during transgression and regression. The high percentage of undulose extension (76.3% among the total monocrystalline; Table 1) may suggest a metamorphic source. The straight and crenulated inter-crystal boundaries in the polycrystalline quartz shows that it originated from metamorphic source rocks (Asiedu et al. 2004). The absence of feldspar and scarcity of rock fragments indicates that the sandstones were probably formed in a lacustrine or marine environment adjacent to

Table 2 Percent framework composition of sandstone of Sarah Formation

Sample no.	Qt	F	L	Qm	Qp	F	Lt (%)
SR01	99.0	—	1.0	90.0	8.0	–	2.0
SR02	98.9	—	1.0	90.0	2.9	–	1.0
SR03	98.8	—	1.0	97.3	1.8	–	1.0
SR04	98.6	—	1.0	96.0	2.0	–	2.0
SR05	98.7	—	1.0	95.5	2.7	–	1.0
SR06	99.2	—	1.0	96.0	5.0	–	1.0
SR07	98.5	—	1.0	94.2	6.0	–	1.0
SR08	100.0	—	–	90.0	7.0	–	3.0
SR09	100.0	—	–	92.0	3.8	–	4.0
SR10	98.1	—	1.9	96.2	2.8	–	1.0
SR11	99.7	—	0.3	94.3	3.7	–	0.3
SR12	99.0	—	1.0	96.0	3.0	–	1.0
SR13	99.7	—	0.3	92.0	6.0	–	2.0
SR14	100.0	—	–	97.3	1.8	–	–
SR15	100.0	—	–	98.2	1.4	–	–
SR16	100.0	—	–	98.6	2.6	–	–
SR17	100.0	—	–	95.4	3.8	–	–
SR18	100.0	—	–	98.2	1.4	–	–
SR19	100	—	–	98.6	1.3	–	–
SR20	98.8	—	1.2	95.7	3.0	-	1.2
SR21	100	—	1.0	94.1	3.5	–	2.0
SR22	98.7	—	1.3	96.5	2.7	–	1.3
SR23	99.2	—	0.80	96.0	3.0	–	0.80
SR24	98.5	—	1.5	95.2	2.5	–	1.5
SR25	100.0	—	–	96.5	3.5	–	–
SR26	100.0	—	–	96.0	3.8	–	–
SR27	100.0	—	–	97.2	2.5	–	–
SR28	100.0	—	–	96.6	2.9	–	–
SR29	100.0	—	–	97.1	2.0	–	–
SR30	100.0	—	–	98.0	1.0	–	1.0
SR31	100.0	—	–	94.3	3.8	–	1.0

Qt total quartz, *F* total feldspar (P+K), *L* total lithic fragments, *Qm* monocrystalline quartz, *Qp* polycrystalline quartz, *Lt* total lithic fragments (including fine grained polycrystalline quartz)

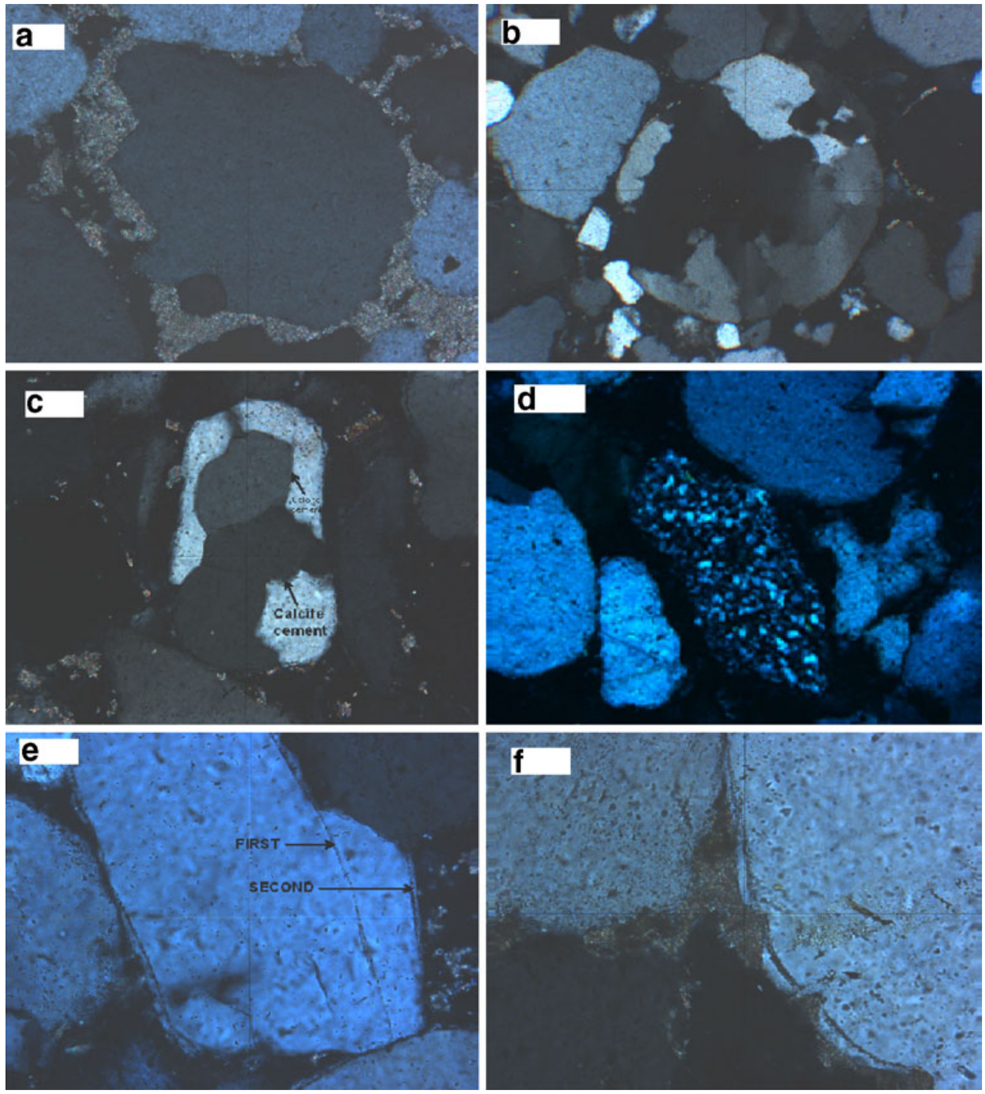


Fig. 3 Corrosion by calcite cements (**a**); Very well-rounded polycrystalline grains with overgrowths(**b**); Sandstone rock-fragment grains (**c**); Chert (**d**); Double quartz overgrowths (**e**); Quartz overgrowths corroded by calcite cements (**f**)

the ice front (Janjou et al. 1996). The presence of few grains of rock fragments (sandstone and chert) indicated their contribution to an appreciable part of the recycled grains in the Sarah sandstone (Fig. 3c, d).

The framework composition data (Table 2) were plotted in Qt-F-L and Qm-F-Lt ternary diagrams (Dickinson and Suczek 1979; Dickinson et al. 1983), including detrital grains excluding micas, opaques, chlorite, heavy minerals, and carbonate grains (Fig. 4). The chert was counted as a sedimentary rock fragments. Figure 4 shows that all the sandstone samples fell in the craton interior field and seemed to be derived from the low-lying granitoid and gneissic sources.

Major elements chemistry of Sarah sandstones was considered to discriminate the depositional tectonic setting of sandstones by Roser and Korsch (1986), Bhatia (1983); and Roser and Korsch (1988). In the Roser and Korsch (1986) and Bhatia (1983) plots exclusively, the Sarah sandstones samples fell into the passive continental margin (Figs. 5 and 6). These sediments seem to be mineralogically mature and deposited in plate interior in a stable continental margin or intra-cratonic basins. Bhatia (1983) further elaborated that such type of sediments are quartz-rich and originated from the old adjacent continental terrains. In the discriminate functions of Roser and Korsch (1988), all the sandstone samples fell in the mature polycyclic continental sedimentary rocks (Fig. 7). The diagram of Suttner and Dutta (1986) between SiO_2 and the total percentage of Al_2O_3, K_2O and Na_2O (Fig. 8) was used to study the paleoclimate signature and the chemical maturity of the sandstones. In the present case, most of the sandstone samples were in humid field with high maturity. The maturity of the sandstones was also supported from the results of petrographic study which indicated sub-rounded and rounded quartz grains with very little rock fragments.

Weathering is an important factor in the study of sandstone provenance and depositional setting. Because in

Table 3 Major elements composition of sandstones of Sarah Formation (percent on weight basis)

Sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	Na_2O	K_2O	P_2O_5	LIO
SR01	98.61	0.270	1.997	0.120	0.06	0.031	0.160	0.021	0.076	0.013	0.59
SR02	99.74	0.146	1.485	0.036	0.06	0.017	0.187	0.018	0.016	0.049	0.82
SR03	97.86	0.067	2.039	0.051	0.06	0.013	0.344	0.041	0.023	0.007	0.99
SR04	99.58	0.142	1.828	0.02	0.14	0.031	0.151	0.036	0.021	0.007	0.71
SR05	97.90	0.157	1.258	0.013	0.06	0.038	0.852	0.016	0.052	0.007	1.77
SR06	96.53	0.083	1.543	0.03	0.06	0.027	0.851	0.028	0.095	0.019	1.83
SR07	99.83	0.045	1.399	0.042	0.11	0.024	0.202	0.06	0.03	0.012	1.18
SR08	98.64	0.000	1.913	0.034	0.06	0.014	0.217	0.039	0.016	0.007	1.08
SR09	98.33	0.314	0.158	0.024	0.05	0.023	0.092	0.049	0.061	0.035	0.85
SR10	97.10	0.283	2.339	0.155	0.06	0.04	0.316	0.009	0.018	0.008	1.24
SR11	96.76	0.054	1.551	0.04	0.06	0.021	0.767	0.033	0.064	0.007	1.70
SR12	98.34	0.367	0.179	0.112	0.12	0.012	0.209	0.015	0.036	0.038	0.81
SR13	97.62	0.506	1.413	0.001	0.12	0.02	0.198	0.052	0.023	0.007	1.31
SR14	98.29	0.061	0.219	0.019	0.06	0.02	0.385	0.024	1.565	0.007	1.25
SR15	99.10	0.371	1.514	0.032	0.09	0.022	0.075	0.012	0.041	0.007	1.20
SR16	98.65	0.055	1.445	0.091	0.06	0.035	0.200	0.034	0.087	0.007	0.45
SR17	98.83	0.118	0.230	0.010	0.17	0.022	0.363	0.044	0.017	0.101	0.64
SR18	97.88	0.075	1.310	0.045	0.06	0.016	0.977	0.051	0.042	0.04	1.43
SR19	99.08	0.073	0.090	0.020	0.13	0.016	0.145	0.041	0.044	0.006	0.33
SR20	98.12	0.134	1.405	0.112	0.09	0.017	0.354	0.023	0.038	0.007	0.89
SR21	98.02	0.058	2.140	0.008	0.10	0.014	0.496	0.052	0.023	0.007	0.78
SR22	99.95	0.255	1.128	0.022	0.11	0.011	0.116	0.053	0.034	0.023	0.48
SR23	99.77	0.317	0.097	0.007	0.06	0.016	0.137	0.024	0.04	0.007	0.38
SR24	99.15	0.027	1.234	0.054	0.08	0.024	0.152	0.019	0.016	0.007	0.68
SR25	97.90	0.042	1.796	0.014	0.08	0.018	0.896	0.052	0.022	0.007	1.35
SR26	99.82	0.146	0.122	0.087	0.09	0.037	0.204	0.036	0.063	0.06	0.47
SR27	98.84	0.074	0.056	0.119	0.11	0.019	0.226	0.048	0.174	0.034	0.51
SR28	96.58	0.218	0.195	0.045	0.08	0.021	0.096	0.048	0.25	0.028	1.06
SR29	96.44	0.028	1.867	0.055	0.06	0.026	0.618	0.004	0.016	0.017	1.12
SR30	97.18	0.002	2.289	0.002	0.06	0.051	0.177	0.041	0.024	0.009	0.60
SR31	97.03	0.091	2.142	0.009	0.06	0.034	0.192	0.006	0.03	0.028	1.04

this period, a change takes place in the composition of major and trace elements. Weathering intensity was evaluated using the formulae CIA (CIA=Al_2O_3/Al_2O_3+ CaO+Na_2O+K_2O) x100 (Nesbit and Young 1982). The average value of CIA for the Sarah sandstone is 63.84% with SiO_2 contents ranging from 96.76–99.74% thus showing a moderate chemical weathering at the source area (Nesbit and Young 1989, Cingolani et al. 2003). As far as provenance is concerned, Nesbit and Young (1982) reported that unaltered basaltic rocks have CIA values between 30 and 40 whereas these are around 50 for fresh granites.

Trace elements are good indicators for studying the provenance and tectonic setting of sandstone (Bhatia 1983; Bhatia and Crook 1986). The discriminate plots of trace elements of depositional tectonic setting of sandstones according to Bhatia and Crook (1986) showed that sandstone samples of Sarah formation are scattered, but most of the samples fall within or around the continental island arc, active and passive margins. Similar results were found in plot of Bhatia and Crook (1986) based on major elements (Fig. 9). Diagram of Floyd et al. (1989) based on TiO_2 v/s Ni suggested that the sandstone samples of the Sarah Formation sediments are derived from Arabian Shields which was predominantly acidic rocks (Fig. 10). Clark-Lowes (1985a,b) also agreed that some of clasts of Sarah Formation were derived from the Arabian Shield.

The trace elements ratio was used to recognize provenance and environmental conditions in the sandstone samples of study area. In the present study, the ratio of Zr/Ti (0.014 on average) related to type of provenance.

Table 4 Trace elements composition of sandstones of Sarah Formation (ppm)

Sample no.	Ba	Ce	Co	Cr	La	Li	Ni	Pb	Rb	Sc	Sr	Th	V	Y	Zr
SR01	50	13.75	0.7	4	6.3	1.3	2.8	8.5	1.4	0.7	30.1	5.3	5	3.42	4.1
SR02	10	10.25	0.1	2	4.6	0.5	0.4	5.2	0.2	0.4	24.8	1.6	3	2.68	3.1
SR03	20	9.22	0.2	3	4.1	0.7	0.4	17.9	0.2	0.4	22.7	1.3	3	3.11	2.6
SR04	60	14.8	0.4	3	6.7	13.9	1.8	7.6	0.8	0.5	36	4.2	4	2.91	4
SR05	10	8.39	0.4	2	3.8	0.5	1.3	4.8	0.3	0.6	27.7	1.2	3	2.27	2.3
SR06	10	8.14	0.3	3	3.7	0.4	1.1	8.4	0.4	0.5	24.4	1.1	4	2.97	2.1
SR07	20	11.95	0.2	2	5.2	0.4	0.6	5.1	0.2	0.4	26.6	1.3	2	2.72	2.3
SR08	20	12.4	0.3	3	5.6	0.8	1.2	10.4	0.7	0.5	27.5	2.4	4	3.27	3.5
SR09	10	8.51	0.1	2	3.7	0.3	0.2	9.9	0.1	0.2	18.7	2.1	2	2.6	4.0
SR10	20	17.7	0.9	5	7.9	1.6	3	8.5	1.6	0.8	37.1	3.8	7	4.0	5.0
SR11	10	13.75	0.1	2	6	0.5	0.5	18.9	0.1	0.4	33.6	2.5	3	2.81	3.3
SR12	20	15.55	0.4	2	6.8	0.4	1	22.4	0.4	0.5	39.6	9.9	4	3.88	6.5
SR13	10	15.1	0.1	2	6.7	0.3	0.5	18.6	0.1	0.5	32.3	5.5	2	4.23	6.1
SR14	10	10.4	0.2	2	4.5	0.3	0.4	9.7	0.2	0.4	26.4	1.6	2	2.48	2.9
SR15	100	14.35	0.2	2	6.2	0.9	0.5	14.9	0.1	0.4	36.6	2.7	3	4.34	5.6
SR16	30	8.95	0.9	2	3.9	0.4	1.7	20.5	0.3	0.5	34.8	1.7	2	3.3	2.4
SR17	20	8.5	0.5	3	3.7	0.6	0.8	17.8	0.2	0.4	59	1.1	4	2.34	2.3
SR18	120	12.05	0.6	4	5.1	0.7	2.1	13.2	1	0.6	42.7	2.6	4	3.85	3.4
SR19	10	12.4	0.2	2	5.1	0.3	0.8	8.5	0.4	0.4	26.9	2.0	2	2.87	3.4
SR20	30	9.84	0.4	3	4.1	0.8	1.7	22.8	1	0.5	31.2	1.5	4	2.98	3.1
SR21	20	12.9	0.3	4	5.5	1.0	1	20.7	0.2	0.5	26.5	2.0	4	4.25	2.9
SR22	20	14.6	0.1	2	6.2	0.5	0.4	19.7	0.1	0.4	35.5	5.0	3	4.49	6.7
SR23	20	12.5	0.1	2	5.4	0.3	0.4	15	0.1	0.4	32.4	2.7	2	3.6	4.0
SR24	10	10.35	0.2	2	4.4	0.4	0.6	13.3	0.2	0.4	27	2.0	2	3.53	4.8
SR25	20	11.05	0.4	3	4.8	0.5	1.2	6.3	0.2	0.5	35.6	1.5	3	2.4	2.5
SR26	20	11.7	0.2	1	4.9	0.5	0.7	16.6	0.2	0.4	30.2	2.6	3	3.74	5.5
SR27	10	10.7	0.1	1	4.5	0.4	0.3	12.2	0.1	0.3	27.7	1.6	2	2.81	3
SR28	20	12.4	0.1	2	5.1	0.8	0.6	12.2	0.3	0.4	28.5	2.3	2	3.36	3.7
SR29	10	10.1	0.3	3	4.3	0.7	0.9	17.3	0.4	0.5	27.4	1.4	3	4.32	2.9
SR30	30	10.7	0.2	4	4.6	1	0.6	24.7	0.4	0.5	28.7	1.7	5	4.93	3.1
SR31	20	8.74	2.6	3	3.8	0.5	1.6	9.5	0.4	0.5	22.8	1.2	3	3.66	2.8

According to Taylor and Mclennan (1985), the low Zr/Ti ratios (0.067 on average) indicated the composition of the upper crust. Boryta and Condie (1985) also reported that Zr/Ti ratios (0.14) related to granitic or clastic sediments and Zr/Ti ratios (0.024–0.034) for andesite in the provenance. They also mentioned that the variation in the Zr/Ti ratio is related to provenance change and not to climatic changes. The mean Rb/K ratio of 0.0016 in sandstone samples showed low concentrations of Rb. The low value of Rb/K ratio in sandstone samples was related to fresh water deposits (Scheffler et al. 2006). In the present study, the Rb/K ratio generally decreased upwards thus indicating that the lower part is more saline as compared to upper part of the Sarah formation. The V/Cr ratio of 1.29 (in present study) indicated that the sediments were deposited either under oxic or reducing conditions. Jones and Manning (1994) further suggested that V/Cr ratios below 2 indicates oxic conditions in the water overlying the sediment. Generally, low Rb/K and V/Cr ratios are characteristic of sedimentation under glacial climate conditions in brackish and oxic sedimentary environments (Scheffler et al. 2006). In the present study, the variation in trace elements and CIA values from bottom to top indicated that after glacial events, the major channels changed the old course and deposited the sediments in different ways which also changed the nature of chemical weathering.

Other elements such as Pb (13.59 mg/l, average) and Ni (1.0 mg/l, average) showed their relationship with phyllosilicates rocks. The high Zr (3.67 mg/l, average) content may indicate recycled or fractionated sediments (Basu et al. 1982; McLennan et al. 1993). On the basis of Zr results, it is evident that the Sarah sandstones are derived from old

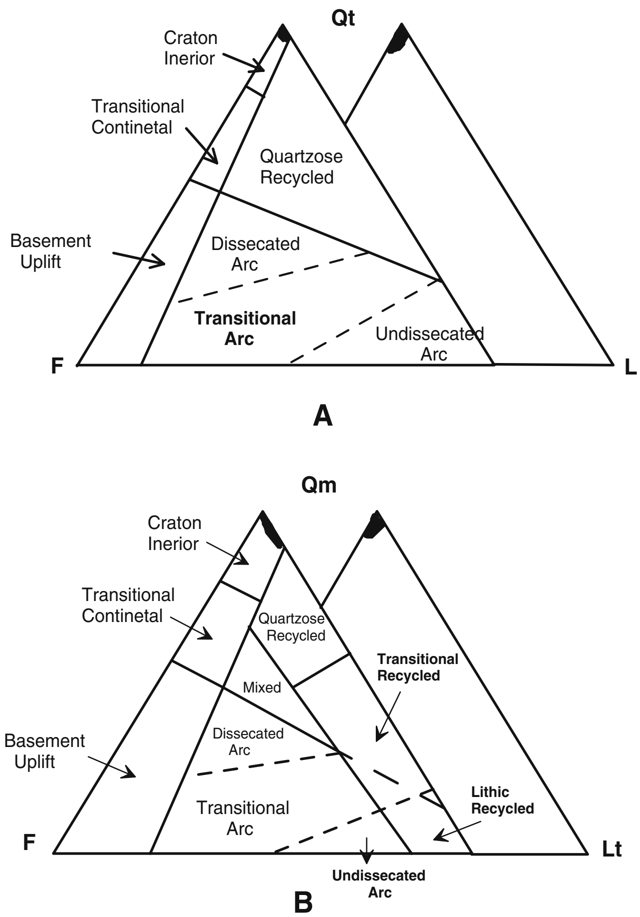


Fig. 4 **a** QFL and Qm-F-Lt plots and **b** provenance fields of Dickinson et al. (1983)

upper continental crust. McLennan et al. (1990) suggested that upper continental crust type of provenance mostly consist of old stable cratons and old continental foundations of active tectonic settings.

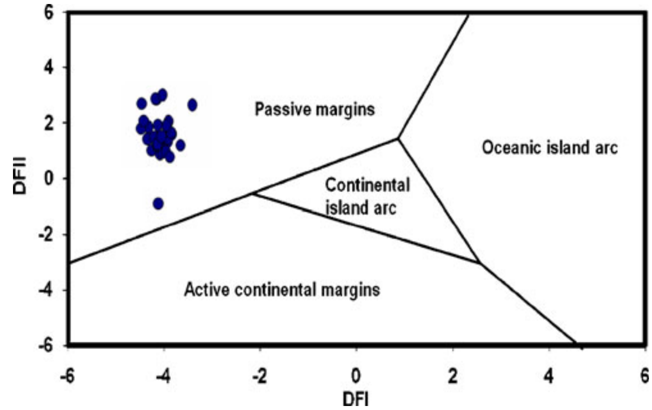


Fig. 6 Discriminate function diagram for tectonic setting of sandstones from Sarah Formation (after Bhatia 1983)

During the course of petrographic study, some diagenetic features in the form of cements, grain contacts, and overgrowths were identified as indicators of provenance and diagenetic events. The study showed that diagenetic alteration was due to cements (clay, calcite, iron oxides, and quartz overgrowths).

The presence of remnant of inherited quartz cement in the form of overgrowth around some of the quartz grains (Fig. 3b) indicates that the grains were recycled from sedimentary rocks of the area. The quartz overgrowths are more abundant in the glacial or fluvial incised-valley (El-ghali et al. 2006).

Double quartz overgrowth indicated that the source area contributed an appreciable part of the recycled grains to the Sarah sandstone (Fig. 3e). These quartz grains seem to be the second cycle grains derived from sedimentary rocks, but most of these grains might have lost their overgrowth by abrasion either during transportation or winnowing by sea. Furthermore, the post-depositional diagenetic events such as

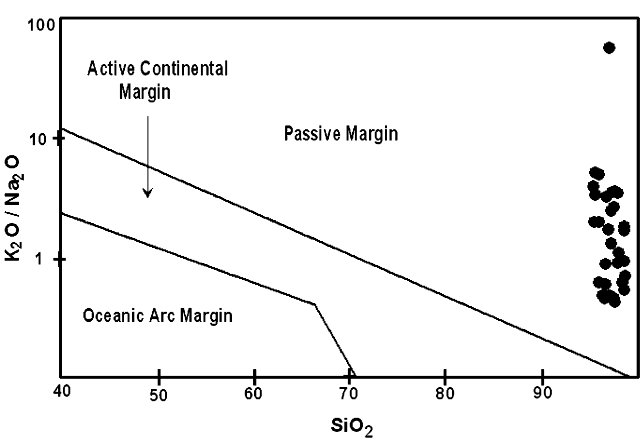


Fig. 5 Tectonic discrimination diagrams of sandstones from Sarah Formation. (after Roser and Korsch 1986)

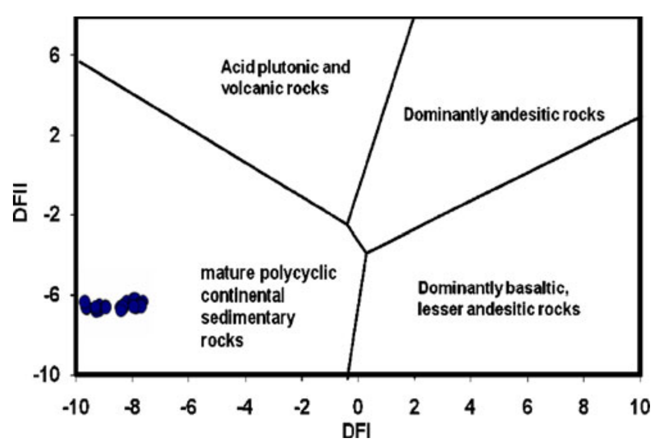


Fig. 7 Provenance discrimination diagrams of sandstones from Sarah Formation (after Roser and Korsch 1988)

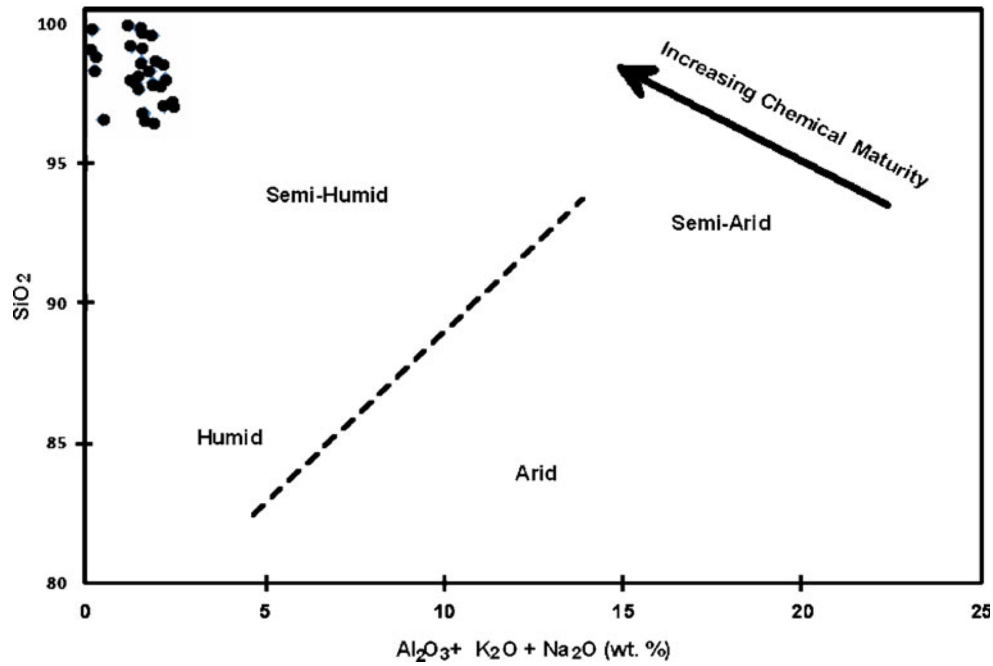


Fig. 8 Chemical maturity of the Sarah sandstone expressed by bivariant plot SiO_2–(Al_2O_3+K_2O+Na_2O) fields (after Suttner and Dutta 1986)

corrosion destroyed the overgrowths of quartz grains. These interpretations are supported by the absence of feldspar, rock fragments, and corrosion of quartz overgrowths in the present sediments. Similar interpretation were drawn by Bernet et al. (2007) from Silurian quartzarenite in south-eastern New York State and El-ghali et al. (2006) from incised valley in upper Ordovician of Murzuq basin, SW Libya.

Clay minerals (kaolin) in the sandstone occur as pore lining, pore filling and kaolinization of unstable detrital grains (Fig. 2). This kaolinization could be due to influx of meteoric water and marine pore water. Sandstone grain coating clay having a grain bridging texture suggested the mechanical infiltration of water (Matlack et al. 1989). Walker (1979) and Ketzer et al. (2003b) stated that grain–bridging clays indicates that infiltration occurred within the phreatic zone, close to fluctuating water table. El-Ghali (2005) reported the formation of glacial and fluvial incised. Such phenomena probably reflect the contemporary warmer and more humid climatic conditions, which were established during paraglacial times.

Calcite occurred as blocky, poikilotopic and pore-filling cement that replaced partially or totally detrital quartz and other detrital grains in loosely packed sandstones. Such type of evidence might occur by marine pore-waters during relative sea level rise. The main source of ions needed for calcite cementation is sea water (Morad 1998). The sandstone, having iron oxide as a cementing material, deposited in the marine environments suggests that the source of iron oxide is from the geochemical zone lying below the sea floor (Berner 1981).

Conclusions

The studied area has no basal sequence and the exposed sandstones were considered as middle to upper part of the Sarah Formation. The presence of medium to fine grains, absence of feldspar and present of few rock fragments indicated the occurrence of braided river deposits. Using the integrated petrographical and geochemical studies, the results indicated that provenance is a complex of granite, metasedimentary and pre-existing sedimentary rocks. Sarah sandstone was deposited on a passive margin that has large amounts of mature sediments from the source areas. Sedimentary rock fragments (chert and sandstone grains)

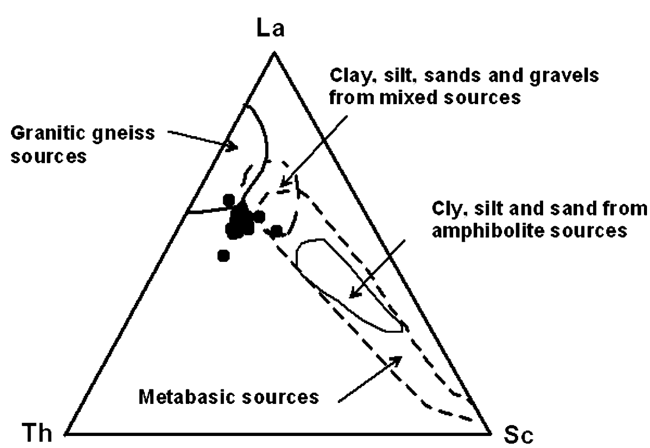


Fig. 9 Relationship between La, Th and Sc for discrimination fields of tectonic setting for Sarah sandstones (after Bhatia and Crook 1986)

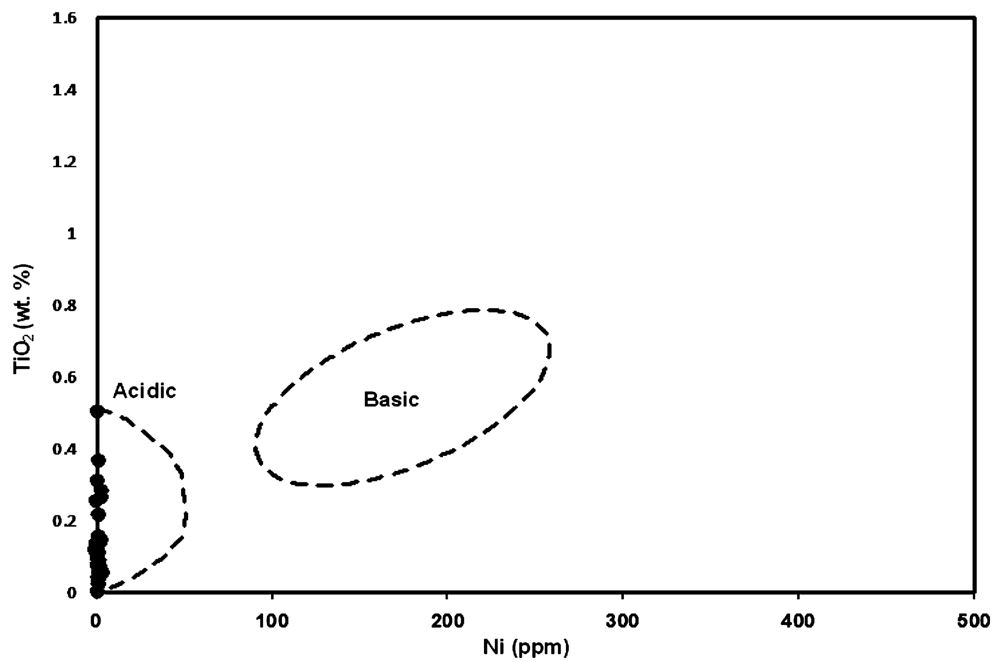


Fig. 10 Relationship between TiO_2 wt.% and Ni ppm content for Sarah Formation (after Floyd et al. 1989)

and double silica overgrowths and other diagenetic features strongly supported the existence of sedimentary rocks in the source areas.

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